Robotic Lunar Lander Development Project Status

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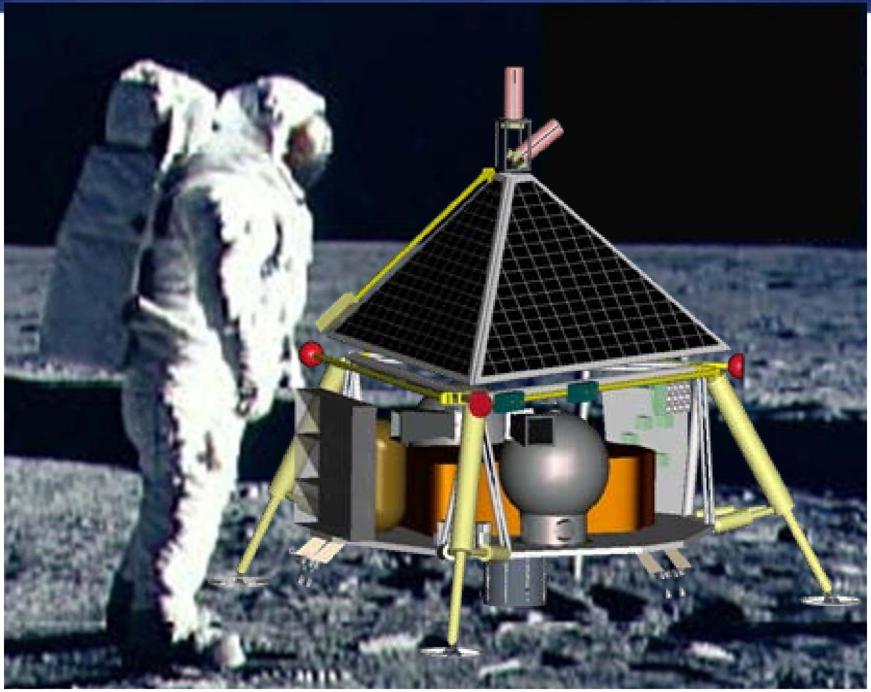

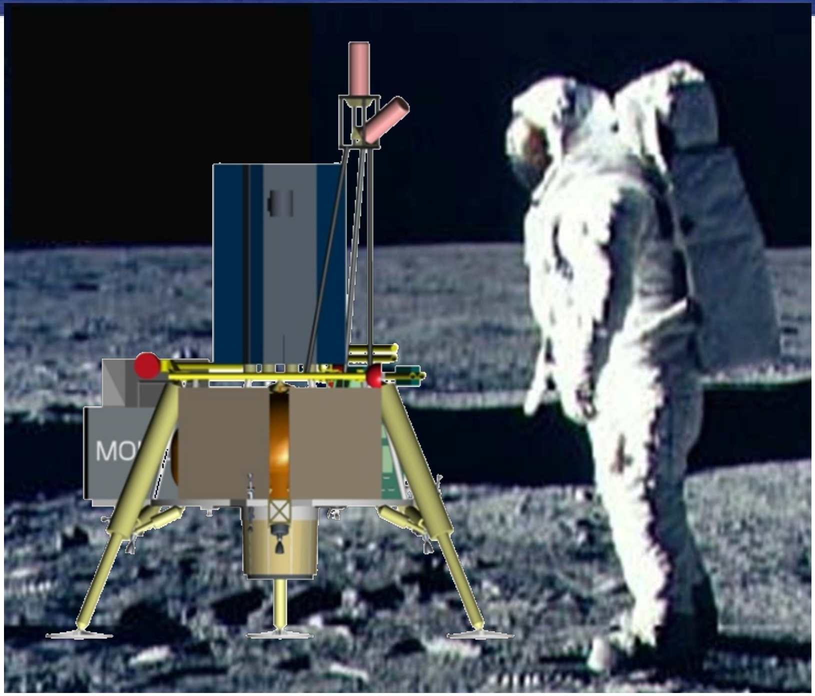

Project Description

Lunar Science mission in pre-formulation performing engineering tests and risk reduction activities to support the development of a small lunar lander for lunar surface science.

March 1, 2010

Flight Robotic Lander Risk Reduction

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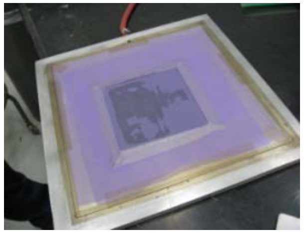
Performing extensive engineering analyses and tests to reduce risk in the development and implementation phases of the project

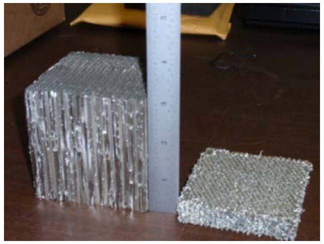
- **Robotic Lander Test Bed**: Hardware in the Loop (HWIL) testing with landing algorithms and thruster positions
- **GNC Test Bed**:Closed-loop, real-time bench testing with the integrated development and test system.
- **GN&C**: validation of landing algorithms with simulations and HWIL
- **Propulsion**: thruster testing in relevant environment, pressure regulator valve performance characterization in relevant environment
- **Thermal**: variable heat transport and lunar heat rejection testing
- **Structures**: composite coupon testing, lander leg stability testing
- **Power**: thermal and life battery testing
- **Avionics:** testing of a low power, high speed communications, and large data storage capacity processor

LN-200S IMU

Radar Altimeter



Composite test panel



3” Core honeycomb structure material crush test

Li-CoAlO$_2$ Alloy Battery

Incremental Development Approach for Flight Robotic Lander Design: Phase 1 (Cold Gas)

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Robotic Lander Testbed - Cold Gas Test Article (Operational)

- Completed in 9 months
- Demonstrates autonomous, controlled descent and landing on airless bodies
- Emulates robotic f**light** lander design for thruster configuration in 1/6th gravity
- Incorporates **flight** algorithms, software environment, heritage avionics, and sensors
- Gravity cancelling thruster provides for reduced gravity operations that can vary with throttling
- Flight time of 10 seconds and descends from 3 meters altitude
- Utilizes 3000psi compressed air for safety, operational simplicity, and multiple tests per day
- 3 primary and 3 ACS thrusters

Robotic Lander Testbed - Cold Gas Test Article available now to International Partners and industry for hardware demonstration, software and model validation or technology testing

Provides a platform to develop and test algorithms, sensors, avionics, and systems to support autonomous landings on airless bodies, where aero-braking and parachutes are not options (e.g. the moon, asteroids)

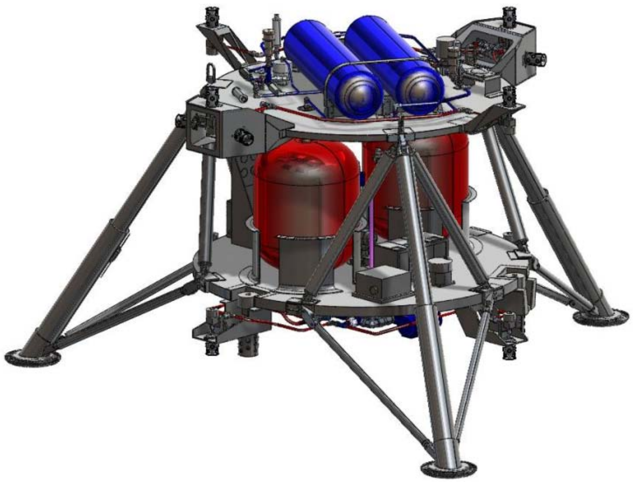
Cold Gas Test Article in Flight Demonstration Testing

*Test bed provides for **autonomous closed loop** control to demonstrate landing capability on airless bodies to build confidence and reduce overall risk.*

Incremental Development Approach for Flight Robotic Lander Design: Phase 2 (Warm Gas)

Warm Gas Test Article (Summer 2010) adds to Cold Gas Test Article Functionality:

- Began WGTA September 2009 ; Completed Critical Design Review March 2010
- Designed to emulate Robotic **Flight** Lander design sensor suite, software environment, avionics processors, GN&C algorithms, ground control software, composite decks and landing legs
- Longer flight duration (approx. 1 min) and descends from 30 meters to support more complex testing
- Can accommodate 3U or 6U size processor boards.
- Incorporates cFE which allows for modular software applications , including GNC, for ease of integration and test.
- 12 thruster ACS configuration. Option to only fire 6 ACS thrusters. Provides capability to support testing of hazard avoidance or precision landing algorithms. Emulates pulse or throttle system.
- G-thruster can be set to different g levels between 1 g to zero g for descent. Therefore, can be used to emulate any airless body for descent.



Robotic Lander Testbed - Warm Gas Test Article available in 2011 to International Partners and Industry for hardware demonstration, software and model validation or technology testing

Provides a platform to develop and test algorithms, sensors, avionics, software, landing legs and integrated system to support autonomous landings on airless bodies, where aero-braking and parachutes are not options

Flight Software: Incremental Approach to Developing and Testing Landing Algorithms

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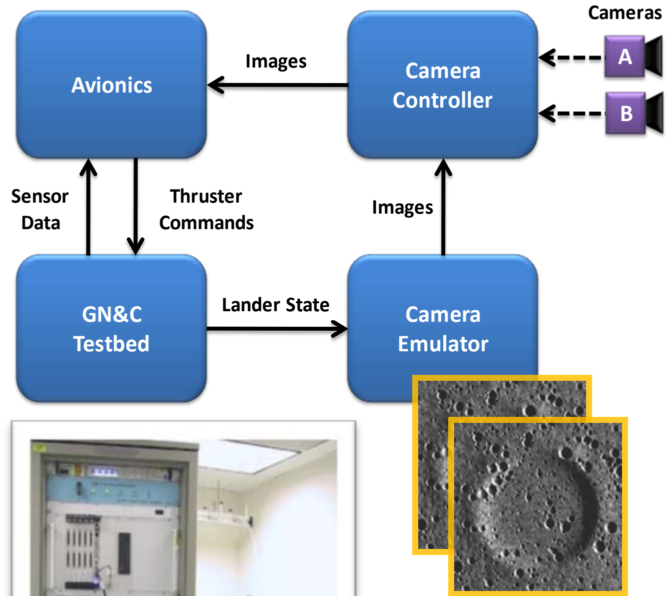
Development and testing of software for real-time Guidance Navigation & Control Landing algorithms reduces risk for flight Robotic Lander:

- Integrated system for development and testing of real-time lander GN&C software:
  - Develop embedded software for GN&C algorithms designed for descent and landing.
  - Develop and incorporate real-time image processing algorithm to support nulling lateral motion during descent.
  - Execute and test the embedded software in a flight-like avionics processor, characterize performance.
  - Develop GN&C testbed hardware/software that monitors thruster commands from the avionics flight software, models lander dynamics, and injects real-time simulated sensor data and images into the avionics.
  - GN&C testbed includes camera controller and camera emulator to support evaluating cameras and simulating lunar images.
- Three phases of testing lander GN&C software:
  - Closed-loop, real-time testing with the integrated development and test system.
  - Flight testing of GN&C and image processing algorithms with Warm Gas Test Article.
  - Field tests with cameras and camera controller to test image processing algorithm with high rates of lateral motion.

Integrated Development and Test System



Flight GNC: Incremental Development Approach for Validating Algorithms thru Analysis and Test

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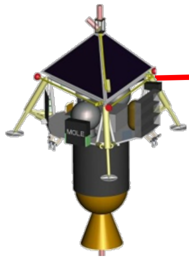
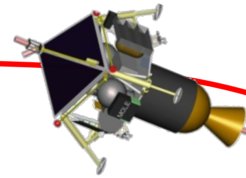
Cruise | ***Braking Burn*** | ***Descent*** | ***Terminal Descent***



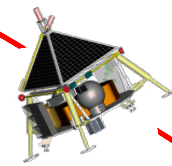
Slow spin, 6 RPM
Spin axis normal to ecliptic

Tested by closed-loop simulation (typical for other missions)



Initial Altitude: 16.6 km
Final Altitude: 3 km
Initial Velocity: 2.5 km/s
Final Velocity: 0.105 km/s
Initial Mass: 1136.6 kg
Final Mass: 456 kg

Tested by closed-loop simulation, numerous Monte Carlos

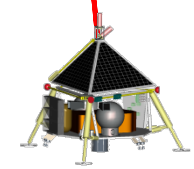


Initial Altitude: 3 km
Initial Velocity: 0.105 km/s
Initial Mass: 380.6 kg

Tested by closed-loop simulation and high velocity field test 2011

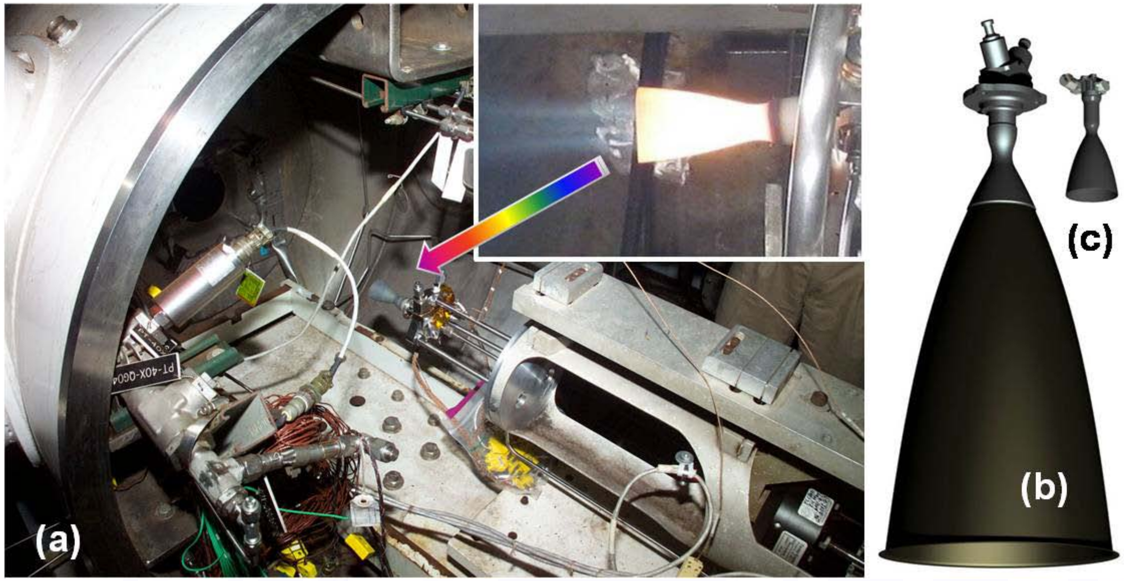
Tested by closed-loop simulation and with Cold Gas and Warm Gas Test articles for HIL closed-loop testing (2009-2010)

Final Mass: 343.5 kg
Touchdown Vel.: < 1 m/s



Flight Propulsion System Risk Reduction Tests

- **Flight Robotic Lunar Lander Thruster Hot-Fire Tests**
  - On September 15, 2009, MSFC completed a matrix of 12 hot-fire tests one week ahead of schedule
  - The test included a mission profile representing a lunar lander duty cycle. This profile spanned 995 seconds and included pulses, coasts, and steady-state burns.
  - The test program fully accomplished its objectives, including evaluation of combustion stability, engine efficiency, and the ability of the thruster to perform a lunar lander duty cycle.
  - Figure (a) is the Test Setup in Vacuum Chamber at White Sands Test Facility for DACS Thruster Hot-Firing and Comparison of Engine Envelope.
  - Figure (b) is a conventional (LEROS 2B) Thruster and figure (c) is the DACS Thruster developed by the Missile Defense Agency
  - Additional tests planned for July 2010
- **Pressure Regulator Testing**
  - Objective of the regulator test is to assess the ability of an available heritage regulator to meet the ILN mission requirements. The regulator is an unmodified commercial unit.
  - Test activities have already begun and will be completed by June 2010.



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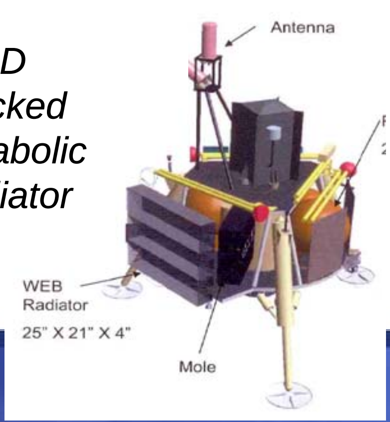
Flight Thermal Management Testing

Compact radiators that reject lander waste heat during hot lunar noon thermal conditions

- Lunar surface temperatures as high as 390K
- Unknown landed attitudes and surface topology; radiator views of hot regolith and the sun
- Lunar dust degradation of radiator optical properties
- Completed thermal performance analysis of standard and novel radiators, locations/orientations and enhancements and key sensitivities. Two baseline options beginning prototype radiator fabrication.
  - Horizontal flat radiator with removable, protective dust cover
  - Stacked, vertical parabolic, radiator with attitude adjustment capability

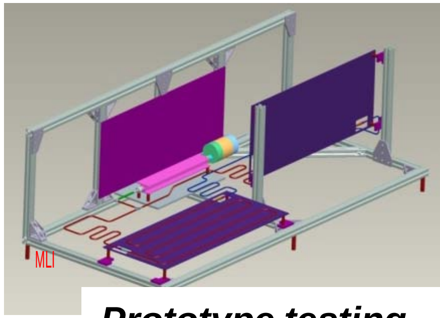
ALSEP Magnetometer Stacked Parabolic Radiator

RLLD Stacked Parabolic Radiator



Passive, variable conductance heat transport capability that thermally couples/decouples the main electronics compartment with heat rejection radiators

- ~5kg of power system mass for each watt of heater power required during lunar night
- Shadows ranging from 14 earth days to permanent
- Lunar surface temperatures from 100 – 390K
- Concept studies at multiple suppliers examined various thermal switch/transport technologies.
- Two loop heat pipe concepts and one variable conductance heat pipe concept selected for fabrication & testing



Prototype testing

Radiator
COND
vapor
LHP/VCHP
liquid
EVAP
RES
WEB
Thermal Isolators
Spacecraft